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Abstract

The use of wireless location technology and mobile phone data appears to offer a broad range of new opportunities for sophisticated applications to traffic management and monitoring, in particular incidence management. Indeed, due to the high market penetration of mobile phones, it allows the use of very detailed spatial data at lower costs than traditional collection techniques.

Albeit recent, the literature in the field is wide-ranging, though not adequately structured. The aim of this paper is to provide a systematic overview of the main studies and projects addressing the use of data derived from mobile phone networks to obtain location and traffic estimations of individuals, as a starting point for further research on incidence and traffic management. The advantages and limitations of the process of retrieving information about location and transportation parameters from cellular phones are highlighted. The issues are presented by first providing a description of the current background and data types retrievable from the GSM network. Furthermore, various

notable studies and projects carried out so far in the field are analyzed, which leads to the identification of important research issues connected with the use of mobile phone data in transportation applications. Relevant issues concern, on the one hand, factors that influence accuracy, reliability, data quality and techniques used for validation, and on the other hand, the specific role of private mobile companies and transportation agencies.

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INTRODUCTION

Location-based digital information – often originating from mobile phone data – has gained much popularity in recent years as a real-time operational vehicle for urban, environmental and transport management. Interesting applications are inter alia the use of private or public spaces by individuals (see, e.g., Calabrese et al., 2001), the concentration of people in a city (see, e.g., (Reades et al., 2009)), the activity spaces of commuters (see Ahas et al., 2006), non-recurrent mass events such as a popfestival (see, e.g.,Reades et al., 2007), the entry of tourists in a certain area of attraction (see e.g., Ahas et al., 2007, Ahas et al., 2008), or the estimation of spatial friendship network structures (see Eagle et al., 2009). Especially in the transportation sector, the potential applications are vast, and consequently, the use of cell phone data has shown a rapid increase in urban transport applications. These data offer a rich source of information on continuous space-time geography in urban areas. They can be used for daily traffic management, but also for incidence management, for instance, in case of big fatalities, terrorist attacks, or mass social events such as festivals or demonstrations.

In the present paper we will address in particular the use of cell phone data for incidence and traffic management in urban areas. The main question to be addressed is how to anticipate and control unexpected events in a transportation system, either on road segments or entire networks? Effective and timely control measures call for real-time detailed data on traffic movements. The possibility offered by micro-electronic devices to identify the geographic positions and flows of people opens unprecedented ways of addressing several policy issues such as urban security, incidence control, organization of services for citizens, traffic management, risk management and so on.

In particular, the opportunity to gather real-time data about location and movements by means of mobile (or cell) phone activities may have an enormous impact on traffic management, given also the interests that private telecommunication companies might have in this market. Moreover, it immediately calls for real-time applications to city management, especially in regard to the optimization and the regulation of the transportation system.

Intelligent Transportation Systems are based on the concept of a dynamic equilibrium between traffic demand and transportation supply. This might be achieved by means of a system able to orient its performance to the request that people have to move, in order to maximize the capacity of the system and to minimize the waste of energy and resources(Cascetta, 2009).

Consequently, a system able to forecast the demand and to anticipate its evolution is needed. Presently, a lot of efforts have been made to obtain models capable of forecasting traffic demand (econometric demand forecasting models, neural and Bayesian networks, stochastic processes, etc.) and to understand the way it moves on transportation networks (traffic flow models, etc.). The problem is that all these efforts have been only marginally tested on real and complex sites, since the cost needed to gather the huge amount of data required is in most cases unaffordable. As an example, the US Government has recently funded the very big NGSIM project (US Department ofTransportation, 2008)) aimed at providing, to the world's research community, data to test and to develop all possible traffic-related models. Albeit invaluable for very specific transportation applications, these data are collected by cameras only on short stretches (few hundreds of meters) of a set of roads in North America.

In recent years, a new typology of data deriving from mobile phones, and in particular from the GSM network, has attracted the attention of researchers, thanks to the idea of the big amount of collectable data at the individual level, and the possibility to obtain high levels of accuracy in time and space. These features make mobile phone data ideal candidates for a large range of applications, in particular in the transportation field.

The history of GSM network is quite recent: in 1982 The European Commission on Postal and Telecommunication Administrations created the GSM (Groupe Special Mobile) to develop Second Generation Standards for digital wireless telephone technology (GSM Association, 2009). In 1987 a memorandum of understanding was signed among 13 countries to develop the cellular system. The GSM (Global System for Mobile Communications) network was launched for the first time in 1991 and already in 1993 there were over a million of subscribers in 48 countries operated by 70 carriers (Emory University, 2009). Now in 2009, 80% of mobile market uses GSM in more than 212 countries, reaching over 3 billion people, (PR NewsWire, 2009)). Recent market surveys show that cellular phone penetration attains and in some cases exceeds 100% (Caceres et al., 2008).

Since mobile phones moves with people and vehicles, big market penetration is one of the advantages of the use of mobile technology for estimating traffic related parameters, once known the location of the device.

The first occasion leading to seriously consider the location capabilities of mobile network stems from European and American regulations regarding electronic communications networks and services: public telephone network operators receiving calls for the emergency calls number should make caller's location information available to authorities in charge of handling emergencies (European Commission, 2002). These regulations motivated telecommunication companies to investigate the network capabilities of determining the location of fixed and mobile users.

Therefore, from the middle of 90s, several studies and projects have been carried out, and in particular over the past decade, a number of research studies and operational tests have attempted to develop wireless location services in sectors like tourism, energy distribution, public transportation, urban planning, disaster management, traffic management, etc. Indeed, many fields nowadays require the use of location technology, and in many cases this need is inducted by the increasing speed in which technology grows. Motivation for this paper is the need to systematize the literature regarding the use of mobile phone data in the estimation of traffic parameters.

Within this background the aim of this contribution is to provide a review of past studies, projects and applications on wireless location technology, highlighting the advantages and limitations of the process of retrieving location information and transportation parameters from cellular phones, and trying to clarify: (i) which data types can be retrieved from the GSM network and how are they are currently used; (ii) whether it is possible to individuate a *fil rouge* among the number of studies in the field; (iii) which are the main research issues connected with the use of telecom data in transportation applications.

This paper is organized as follows: in the next section a short description of the most used mobile phone location methods is provided, while the literature review is presented in a subsequent section. Next, an illustrative application to the city of Amsterdam is offered. Main unsolved research issues and conclusions are discussed in the last two sections.

MOBILE PHONE LOCATION METHODS

In order to understand which are the mechanisms allowing to derive the location of a mobile phone from the signals it sends to the network, it is worth clarifying how the GSM network works (www.gsmfordummies.com, 2009). It is relevant to note that in the present study novel kinds of network such as UMTS (Universal Mobile Telecommunications System) will not be considered.

As shown in Figure 1, physically the Base Transceiver Station (BTS) is the Mobile Station's (the mobile phone, aka handset) access point to the network. A cell is the area covered by 1 BTS (not visible in the figure). The network coverage area is divided into set of cells, named Location Areas (LAC). The BSC (Base Station Controllers) is a device that controls multiple BTSs. It handles allocation of radio channels, frequency administration, power and signal measurements from the Mobile Station. The heart of the GSM network is the Mobile Switching Centre (MSC). It handles call routing, call setup, and basic switching functions. An MSC handles multiple BSCs and also interfaces with other MSC's and registers. Location Management from GSM network is possible by means of a system of databases, the HLR (Home Location Register) and the VLR (Visitor Location Register). The HLR is a large database that permanently stores data about subscribers, including current location of the mobile phones. The VLR is a database that contains a subset of the information located on the HLR. It contains similar information as the HLR, but only for subscribers currently in its Location Area. The position of a mobile phone is derived from an automatic process that maintains the network informed about the phone location, depending on the phone status.

By means of a system involving the exchange of signaling messages between the phone and the network, the so-called Location User process is able to determine the position of the cellular at the Cell-ID level. The operator knows the coordinates of each cell site and can therefore provide the approximate position of the connected mobile. To overcome this approximation, two methods are acknowledged in the literature (Promnoi et al., 2008); (i) Received Signal Strength (RSS) methods, a technique that estimates the position of a mobile phone by matching the signal strength with the neighboring reference points; (ii) triangulation, based on the difference of the arrival instant of the signal from the same handset to a set of different receiving base stations. The mobile station measures the arrival time of signals from three or more cell sites in a network. The network measures the transmission time of these signals from the relevant cell sites. Combining these two pieces of information it is possible to estimate the position of the mobile phone.

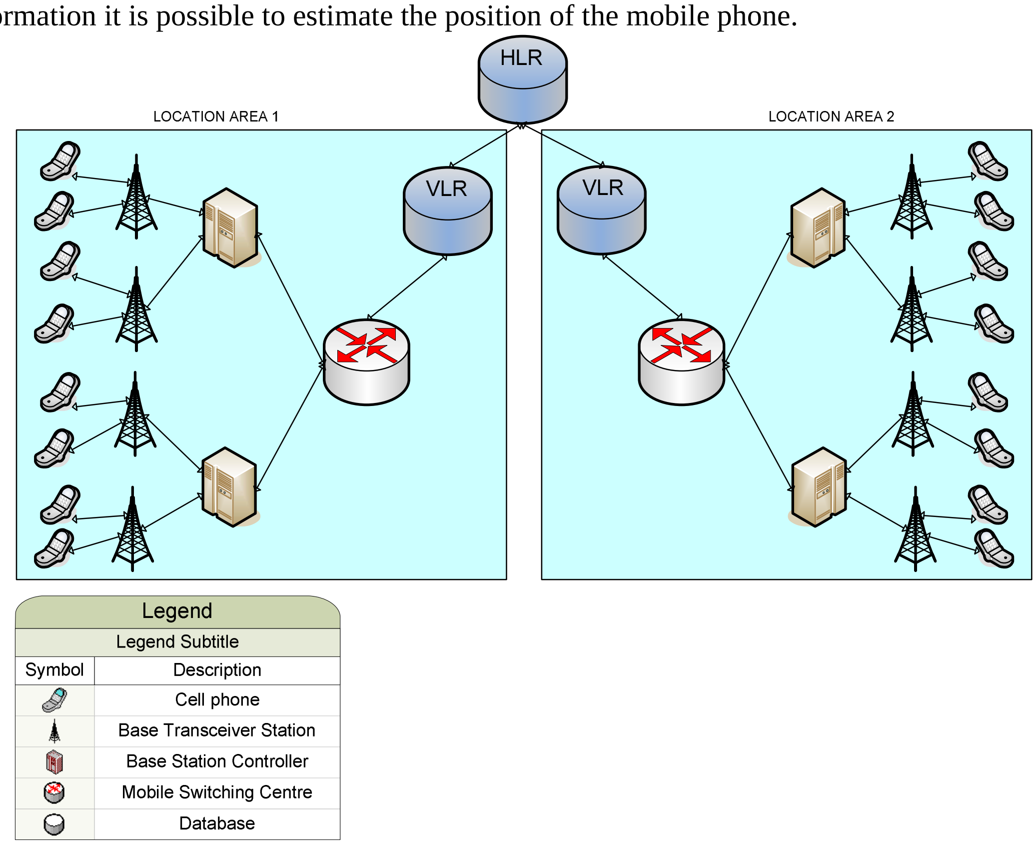

Figure 1 **GSM network scheme**

These methods need the network to be synchronized and require additional network elements which are not strictly necessary for GSM communication, SMS (Short Message Service) or IP traffic. For this reason, cell-based location data, without any form of improvement through RSS or triangulation, are currently the most used.

Apart from location information, GSM network provides mobile phone activity parameters, which inform about the rate of use of the network. The most used activity parameters to estimate transportation parameters are handovers, cell dwell time and communication counts. A good comprehensive review is given in (Caceres et al., 2008) and (Ratti et al., 2006).

Handovers (also called hand-off) refer to the switching mechanism of an on-going call to a different channel or cell. It is the mechanism of managing a permanent connection when the phone moves through two cells of the network. Hereby the phone call changes from one base station to the other without quality loss. This information is stored in the above mentioned HLR and VRL network databases. Together with the Mobile Switching Centers (MSC) they provide the call routing and roaming capabilities of the GSM network.

Cell Dwell Time (CDT) is the duration that a cellular phone remains associated to a base station between two handovers. This parameter is used in the literature referring to each individual cell, and thanks to the comparison among multiple adjacent cells it allows estimating traffic congestion.

The actual use of the network also provides useful indicators. The standard unit of measurement of telephone traffic used by most network operators is Erlang. One Erlang is one person hour of phone use. Erlang data is aggregated and anonymous data in terms of usage time and depends on the number of communications and their duration.

Telecom operators also measure a range of additional traffic features, either for billing, network planning and network quality control. They include the number of new calls, the number of terminating calls, the average call length or the number of SMS.

In the next section it will be explained how such cell-phone parameters have been used in the literature so far to retrieve traffic parameters.

REVIEW OF PROJECTS USING MOBILE PHONE DATA FOR TRAFFIC PARAMETERS ESTIMATION

In this section a short description of the most important field test deployments and simulation studies aimed at the estimation of traffic-related parameters is provided. Details are offered in Table 1.

Since there has been quite a number of review studies in the field, for a thorough description of the main projects and simulations studies, the reader may refer to (Fontaine et al., 2007), and (Caceres et al., 2008), which only exclude the most recent projects. Here the main features of the studies will be highlighted.

The first recorded attempt and big project investigating mobile phones as vehicle probes is the CAPITAL project (Cellular APplied to ITS Tracking And Location), which started in 1994 (University of Maryland Transportation Studies Center, 1997). It has been the first big project using an extensive set of data from a mobile company, and obtaining position through triangulation methods. Unfortunately, the location accuracy of about one hundred meters was not sufficient to obtain reliable traffic information (see Table 2).

Several other studies followed, like the US Wireless Cooperation Tests with deployments in San Francisco and Washington D.C. using the RadioCamera technology (Yim and Cayford, 2001; Smith et al., 2001). Together with CAPITAL, these early generation systems based on wireless signal analyses and triangulation had significant problems in determining true location of the cellular phone and were largely unsuccessful (Fontaine et al., 2007).

After these early attempts there was a shift from wireless signaling analyses to handoff-based techniques. A first European effort to use the mobile cellular network for road traffic estimations based on handovers was initiated in Italy, in a simulation study by (Bolla and Davoli, 2000). Claiming to be the first looking at this field, this study analyzes the use of location information to estimate on-line traffic conditions of important roads and highways by exploiting the presence of mobile phones on board of vehicles. The presence of a cellular terminal could be detected at the vehicle's entrance in monitored roads. This quantity was then used to estimate average vehicle density, flow and speed in every cell.

Another early European example has been found in the UK (White and Wells, 2002), where the Transport Research Laboratory (TRL) developed a system to generate journey times and traffic speeds from OD matrices based on billing data from the telecom network. This study only uses a subset of all monitored phones, resulting in a very small sample size.

Then, in recent years in a number of European countries (e. g. France, Belgium, Germany, Spain, Austria, Finland, Italy, UK and The Netherlands) different field tests, simulation studies and evaluations took place. Most of these projects focused on how to obtain reliable travel times and travel speeds from the telecom network.

An extensive study of cellular probes has been carried out within the framework of the STRIP project (System for Traffic Information and Positioning) in Lyon, France (Ygnace, 2001). They evaluated the feasibility of 'Abis/A probing' location technology for travel time estimates. Abis/ A Probing system is a network-based solution that gathers data from the cellular service providers. The system uses Abis and A interfaces, which include algorithms and databases of information to identify the location of a cellular phone. Results were compared with detection loop data, both on an inter-city motorway and an intra-city freeway, with major errors in the second case. A significant relationship between the number of outgoing calls and the level of incidents was found (Caceres et al., 2008).

Another example of travel time estimates was carried out in Finland by the FINNRA (Finnish Road Administration) in 2002 (Kummala, 2002; Virtanen, 2002), with the aim of estimating traffic data from mobile phone data exploiting the signaling messages exchanged between the phones and the network, eventually using License Plate Recognition (LPR) to validate the results(Caceres et al., 2008). There were more accurate results produced when the traffic was monitored over longer stretches of about 10 kilometers. The data was affected by some problems such as parallel roads and pedestrians. Also the location of the base stations was not always optimal to support traffic management information systems.

In 2003, the telecoms carrier Vodafone, in collaboration with the Institute of Transport Research of the German Aerospace Center, used double handovers (combination of data from two successive handovers from the same mobile phone, possible if the call duration is long enough) and signaling data from the network to generate traffic flow and traffic speed around Munich (Thiessenhusen et al., 2003).

LogicaCMG developed in 2004 the Mobile Traffic System (MTS) to monitor traffic speed and provide road authorities with the possibility to manage traffic flows and traffic congestion (www.logica.com, 2009). The system was tested in the province of Noord-Brabant in Netherlands and validated with field data from floating cars, number plate surveys and induction loop detectors.

The British company ITIS Holding developed in 2006 a pilot project based on the 'Estimotion' technique in the province of Vlaanderen in Belgium. They monitored traffic on highways to verify traffic speed between two arterials. Even here the objective was to assess whether data collected from mobile phones (e.g. travel times) provided accurate traffic information. The validation study compared traffic data from cellular floating vehicles with other traffic sources such as single inductive loop detectors and GPS-equipped probe vehicle. The general conclusion was that the technology was quite able to accurately detect the traffic trends over time and per road segment. The prediction was however most accurate in the case of free traffic flow rather than in congested conditions (Maerivoet and Logghe, 2007).

In the TrafficOnLine project in 2006 in Germany, the already mentioned idea of double handovers was used (Birle and Wermuth, 2006). In order to validate the results, double handovers, loop detectors and floating car data (FCD) from taxis equipped with GPS were compared. As a result, it was shown that mobile phones can provide reliable detection of traffic congestion, depending on the covered area. Better results were obtained for motorways compared to urban roads. To improve the results in urban environment information of existing buildings, which were responsible for handovers in overlapping coverage and signal strength of adjacent cells, were used. Problems were limited to a small sample size, because only phones that made sufficient long calls within an entire cell were included. It was concluded that reliable data only could be generated in the case where a single roadway link exists into the border zone between two cells so that it can be uniquely identified.

Enlarging the view outside Europe, the study of Bar-Gera (2007) in Tel-Aviv compared the performance of the WLT data, detection loop data and floating car data to validate travel times. Intervals without congestion showed little variation of mean travel times.

In North America a number of field studies have been carried out on the use of handovers to estimate traffic features. In 2003, Airsage deployed a monitoring system in the Hampton road region in Virginia based on cellular handoffs and transitions between sectors of cells to produce traffic speed and travel time. The University of Virginia performed the evaluation in 2005 and found significant errors. It was concluded that, as of December 2005, the Hampton Airsage system could not provide the quality of data desired by the Virginia Department of Transportation (University of Virginia Center for Transportation Studies, 2006; Smith, 2006)

In 2005, in collaboration between ITIS holding and Delcan Corporation, another project was initiated based on the ‘Estimotion’ technology in Maryland(Delcan Corporation, 2009). They used handovers to detect traffic events like congestion and accidents. The data was tested during 2006 by the University of Maryland, which found that average errors were approximately 10 mph on freeways and 20 mph on arterials. The quality degraded significantly during a.m. and p.m. peak periods.

In 2007, the Minnesota Department of Transportation carried out a field test around Minneapolis in collaboration with the telecom operator Sprint PCS network (Liu et al., 2008). The travel times and travel speeds were compared against ground truth conditions.

In 2008, around San Francisco bay area, the Mobile Millenium project was started (Amin et al., 2009), whose aim is “to design, test and implement a state-of-the-art system to collect traffic data from GPS-equipped mobile phones and estimate traffic conditions in real-time”.(http://traffic.berkeley.edu/theproject.html, 2009)

The project has organized a big field test deployment consisting in tracking the location and changes in position of informed users, carrying a particularly equipped Nokia mobile phones inside their vehicles. In exchange, participants receive, free of charge, traffic information on the screen of their mobile. This project is still going on.

In 2007, in a field test in an area around Bangkok in Thailand, researchers developed a methodology for detection and estimation of road congestion using CDT (Pattara-Attikom and Peachavanish, 2007; Pattara-Attikom et al., 2007). CDT from multiple adjacent cells was used to estimate traffic congestion. The sample size includes mobile terminals in active mode (on call) and idle modes (turned on). They classified measurements in three levels of traffic congestion based on duration. The results showed that that the duration of CDT estimated the degree of congestion with an accuracy level between 73 and 85%. However they concluded that many issues need to be solved before actual implementation can take place.

Regarding applications not concerned with travel times or travel speeds, two recent (2007-2008) simulation projects on OD matrix can be found in Spain (Caceres et al., 2007) and Korea (Sohn and kim, 2008) both focusing on generation of traffic flows. The project in Spain concluded that turned-on phones (active and idle modes) of only one operator should be sufficient, and proposes an adjustment factor to transform phone data to vehicle data.

The project in Korea uses a simulated environment for validation. They found that the accuracy of the estimation was less depending on the standard deviation of probe phones changing location than other factors like market penetration and cell dimension.

The Real Time Rome project (Calabrese and Ratti, 2006) is one of the first examples of an urban-wide real-time monitoring system that collects and processes data provided by telecommunications network and transportation systems, in order to understand patterns of daily life in the city of Rome. They address a broad range of research directions like: how do people occupy and move through certain areas of the city during special events (gatherings), which landmarks in Rome attract more people (icons), where are the concentrations of foreigners in Rome (visitors) and if public transportation is effectively where the people are (connectivity).

In (Reades et al., 2007) the authors analyze how cell phone data in Rome can provide a new way of looking to cities as a holistic dynamic system. This approach can provide detailed information about urban behavior. Erlang data normalized over space and time is used to derive spatial signatures, which are specific time patterns of use of the mobile network distinctive of a certain area. They found a mix of clusters that suggest a complex set of relationships between signatures. The visualizations generated an overall structure of the city with a correspondence between the levels of telecommunication and types of human activities. In (Girardin et al., 2008) they explore the use of cell phone network data and geo referenced photos for the presence and movement of tourists with user-originated digital footprints.

In Table 1 an overview of the main information such as data source, promoters, and typology of results of the mentioned field projects is provided, while in Table 2 a focus on the main characteristics of major recent and past projects is offered.

ILLUSTRATIVE APPLICATION FOR AMSTERDAM

In 2007 the Current City consortium (SENSEable City Laboratory MIT; Salzburg University) in cooperation with the Dutch Ministry of Transportation has realized a test system in Amsterdam (Netherlands) for the extraction of mobile phone data and for the analysis of the spatial network activity patterns. This project is strongly related to the earlier projects Mobile Landscapes in Graz (Ratti et al., 2007) and Real-time Rome (Calabrese and Ratti, 2006). In the remainder, it will be explained more in detail, as it is the project from which the authors will start their further research. The project does not focus directly on traffic patterns, but explores space-time relationships of telecom data and assesses its suitability to derive census proxies and dynamic patterns of the urban area, which in turn can be utilized to derive mobility indicators, showing the possibility of extracting near real-time data from cell phone use and to reconstruct the spatial- temporal patterns of the telecom network usage (www.currentcity.org).

The project uses anonymous data of KPN Mobile network. The data, such as Erlang or SMS counts, is used by the carrier to manage network quality. In the study area there are over 1200 cells grouped in 8 LACS. It involves the city of Amsterdam and its surroundings, for an area of about 1000 km^2.

The main research goal in this project is how telecom data can be utilized for understanding presence and mobility in regular situations and during events where entire regulated flows of people are disrupted by an incident or an exceptional occasion like a football match, a music concert, a large celebration or a demonstration. This outcome could then be used to understand how a city or a mobility system can be measured, simulated and actuated to improve the quality of services provided to inhabitants (Vaccari et al., 2009).

Table 1 Summary of studies and field test deployments (in bold the review studies from which specific information has been derived)

Years	Project title (where available) (Reference)	Promoters	Location	Data source	Used cell-phone parameters	Target Traffic estimations	Results
1994-1997	**CAPITAL** *(University of Maryland Transportation Studies Center, 1997)*	Federal Highway Administration Virginia Department of Transportation Maryland State Highway Administration University of Maryland Bell Atlantic NYNEX Raytheon, Farradyne	Washington D.C, USA.	Data from Bell Atlantic NYNEX Mobile's cellular network	Position through triangulation	Traffic Speed	Only 20% of probes generated speeds 100 m position accuracy Not consistent traffic monitoring
1999 2002	*(White and Wells, 2009)*, ***(Caceres et al., 2008)***	Highway Agency UK Transport Research Laboratory BTCell net (O2)	Kent, UK	Billing data from BTCellnet	Initial and ending position of the mobile phone	OD matrix	Small sample size Phones on call Groups able to transmit their position to server
2000	*(Yim and Cayford, 2001)*, ***(Fontaine et al., 2007)***	US Wireless Corporation University of California-Berkeley	San Francisco Oakland, USA	44 h of wireless data from US Wireless	Position of the mobile phone – call duration	Traffic Speed	60 meter mean location accuracy 60% of locations could not be matched to road No usable data generated
2000 2001	*(Smith et al., 2001)*, ***(Fontaine et al., 2007)***	US Wireless Corporation Virginia Department of Transportation Maryland State Highway Administration University of Maryland University of Virginia	Washington D.C., USA	160 phone calls tracked every 2 seconds, generating 4800 data points every minute	Cellular phone position	Traffic Speed	5% of 10-min intervals had no data 6 to 8 mph mean speed estimation error Some intervals had errors > 20 mph Over 20% had significant differences from reality
2001	**STRIP** *(Ygnace, 2001)*, *(Ygnace and Drane, 2001)*, ***(Caceres et al., 2008)***, ***(University of Virginia Center for Transportation Studies, 2006)***	INRETS SERTI French Government SFR carrier (Vodafone France)	Lyon, France	Mobile phone data from SFR	Position from in-vehicle mobile phones Number of phone calls	Journey times Traffic Speed Directions of movement	Inter-city speeds overestimated by 24% to 32 % Little speed variations on inter-city motorway Strong relation between call volume and number of accidents
2002	*(Kummala, 2002)*, *(Virtanen, 2002)*, ***(Caceres et al., 2008)***	Finnish Road Administration Radiolinja	Finland	Mobile phone data from Radiolinja	Time required by each phone to cross a road	Travel time Journey time	Validation with License Plate Recognition (LPR) More accurate results produced when the traffic was monitored over longer stretches around 10 km

					section from the moment it enters the service area of a base station (cell) until the next ***(Error! Reference source not found.)***		Location of the base stations not always optimal
2003	*(Thiessenhusen et al., 2003)*, ***(Caceres et al., 2008)***	Institute of Transport Research of German Aerospace Center Vodafone	Munich, Germany	Mobile phone data from Vodafone	Handover	Traffic flow	Errors between 20 and 30 km/h Phone flows (calls) are closely related to vehicular flows Results based on small sample size
2004	*(Rutten et al., 2004)*	Mobile Traffic Service (MTS) LogicaCMG Vodafone	Noord-Brabant, Netherlands	MTS (Mobile Traffic Service) data from LogicaCMG and Vodafone	Handover Location update	Traffic flows Traffic congestion	High correlation between travel times generated by MTS and by the reference systems. Errors generally low between 3-4 %, with errors of 10-20 % in journey times of 20-25 minutes. Conclusions based on limited results that are publicly available.
2003 2005	*(University of Virginia Center for Transportation Studies, 2005)*, *(Smith, 2006)*, ***(Fontaine et al., 2007)***	Federal Highway Administration Virginia Department of Transportation AirSage inc. University of Virginia	Hampton Road, Virginia	Anonymous mobile phone data from Sprint US carrier	Handovers	Travel speed Travel time	68% of speed estimated had errors > 20mph Not reliable measures Airsage claimed results caused by lack of access to full data
2005	**MIT SENSEable City Laboratory** *(Ratti et al., 2006)*	MIT A1 Mobilkom	Milan, Italy	Anonymous data from a European telecoms carrier	Erlang Network counters	Call density OD of Calls	Real-time visualization dynamics metropolitan area
2005	*(Maerivoet and Logghe, 2007)*	ITIS Holdings Proximus	Flanders Antwerp Belgium	Anonymous Cellular Floating Vehicle Data (CFVD).	Handover	Travel speed	Technology able to accurately detect the traffic trends over time and per road segment. Predictions however most accurate in the case of free traffic flow rather than congested conditions.
2005 2006	*(Bar-Gera, 2007)*	Estimotion Ltd. ITIS Inc. Ben Gurion University	Tel-Aviv Israel	Cell phone data provided from Estimotion Ltd.	Handover	Travel time	Limited data during off-peak hours WLT estimates different between floating car and loop data by 10 to 30% during congested conditions
2006	**Real-time Rome** *(Calabrese and Ratti, 2006)*	SENSEable City Laboratory MIT Telecom Italia	Rome Italy	Cell phone data provided from Telecom Italia Mobile	Erlang	Touristic, pedestrian and vehicle density Travel speed	Broad range of research directions demonstrating a large spectrum of useful applications

2007	*(Liu et al., 2008)*	Minnesota Department of Transportation University of Minnesota Sprint PCS	Minnesota, USA	Cell phone data from Spring PCS Mobile network	Handover	Travel times	Segments with high speeds results within 10 MPH of ground truth In segments with low to moderate speeds the results become occasionally scattered Under and over estimating travel times between AM and PM peak hours where found for some roads
2007	*(Pattara-Attikom and Peacavanish, 2007), (Pattara-Attikom et al., 2007), (Hansapalangkul et al., 2007), (Hongsakham et al., 2008)*	NECTEC NSTDA Thamasat University	Bangkok Thailand	Data from probe mobile phone in vehicles	Cell Dwell Time	Traffic Congestion	Accuracy level congestion estimates between 73 - 85 %. Sample size includes phones in active and idle modes
2008 2010	**Mobile Millennium** *(Liu et al., 2008)*	Nokia, Navteq, and UC Berkeley, California Departments of Transportation	Hayward and Fremont area, California	GPS equipped cell phones	Virtual Trip Lines, Position and speed of mobile phones	Speed and travel time	Provides real-time traffic conditions to end users Free public traffic-information system Deployment, currently testing
2007 2009	**Current City Amsterdam** *(Vaccari et al., 2009)*	Senseable Future Foundation University Salzburg Vrije Universiteit Amsterdam KPN Dutch Department of Traffic Management, (Rijkswaterstaat)	Amsterdam, The Netherlands	Data from Dutch KPN carrier	Network parameters	Spatial network signatures	Use of telecom network data for analysis of the spatial network activity patterns

Table 2 Main field test project characteristics

	CAPITAL	US-Wireless	STRIP	Real-Time	Mobile-Century
Promoters					
Public Agencies	X		X	X	X
Research Institutions	X	X	X	X	X
Mobile phone carrier/company	X	X	X	X	X
Location technology	Triangulation	RadioCamera	Signalling messages	Ad-hoc algorithm based on ToA, TA, CDT, TDoA	GPS
Location accuracy	107 m ***(Fontaine et al., 2007)***	60 m ***(Yim and Cayford, 2001)***	100-150 m ***(Caceres et al., 2008)***	Not available	Same as GPS, 10 m ***(Spinak et al., 2009)***
Useful traffic info	No	No	No	No	Yes
Use of new technology	No	RadioCamera	Abis/A probing	Yes	No
Validation	No	Loop detectors	Loop detectors	No	Loop detectors

The data has firstly been processed to generate different visualizations of the urban dynamics of Amsterdam. The primary features of the data are the weekday–weekend and the day-night pattern which affect all data. The weekday-weekend pattern is more or less pronounced depending on the area itself and appears to follow a rather predictable activity pattern within a certain range of variations. These patterns are in part the result of presence of people in a certain area and of people's mobility, but also of callers' behavior, ranging from the obvious lower network traffic during the night to subtler behavioral caller changes that depend on the callers' context. Figure 2 shows the effect of events on the network traffic. Around Queen's day (30 April), a major city gathering, the network activity peaks in certain areas such as the Rembrandtplein (the blue line), where street parties and celebrations take place, while it subsides in areas such as the World Trade Center (WTC, the red line) which shows typical weekend behaviors.

A more detailed data analysis in the project Current City has been carried out for a selected number of areas that are characterized by different land-use patterns and known differences in terms of how people use the area. The definition of the areas was based on the indications of the best serving coverage map overlapped to land use. The weekly patterns can be seen from the graph in Figure 3. The diagram shows for each day the average traffic (Erlang) over a period of five months (1 January – 30 May 2008). The data are normalized on the averages for comparison. Most areas, with the exception of Rembrandtplein and Arena show a week-weekend pattern. Rembrandtplein does not respect the same pattern, and has a stable-increasing traffic during the weekends. The Arena, the area around the Ajax stadium, has a peak of activity on Sundays during soccer games.

The project Current City has presented the use of telecom data for the analysis of spatial network activity patterns based on a 1 hour interval. Next steps in the project are reduction to 15 minute time interval, a more detailed analysis of data validation and an improvement of visualizations. At the same time, some applications for crowd management, evacuation support for disaster management, incident management based on network activity patterns and traffic management for the inner city of Amsterdam where there are no detection loops will be developed.

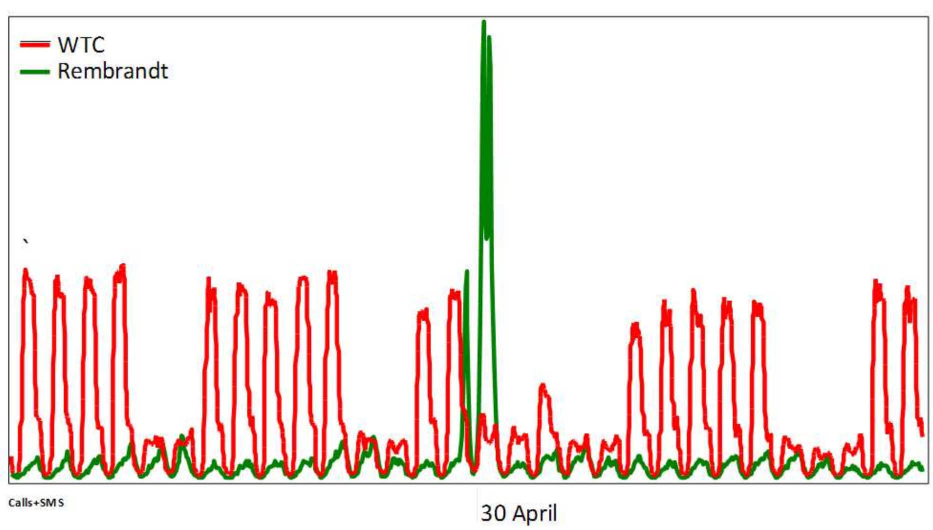

Figure 2 Day-night pattern and weekend pattern for the traffic at WTC and Rembrandtplein (http://www.currentcity.org/)

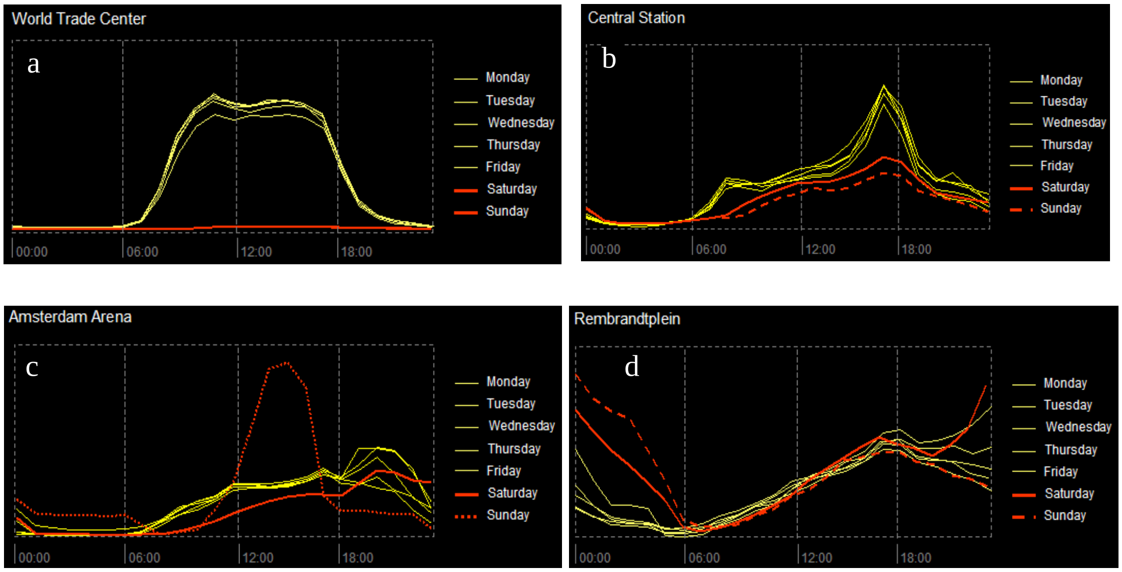

Figure 3 Call intensity in different Amsterdam city areas: a) Business district, World Trade Center; b) Transport hub, Central Station; c) Football stadium, Arena; d) Entertainment nightlife, Rembrandt square. Source (http://www.currentcity.org/)

MAIN RESEARCH ISSUES

Lessons

Road traffic analysis and prediction are two of the most attractive areas of use for mobile network data. Steady growing traffic volumes have led to enormous congestion and mobility problems, especially during the rush hours, both in urban areas and the highway networks.

While traditional measuring methods, such as road loop detectors, camera detection or floating probe vehicles, are effective and precise, there are practical and financial limitations to their use. Detection loops installed under the road pavement are regularly installed on highways but their application in urban environments appears as unfeasible given the number of roads that need to be monitored and the complexity of installation. Similar concerns can be raised for detection cameras, which are a feasible option for a limited number of measurement points. There is however an increasing need for less expensive monitoring systems and effective and reliable information systems.

It is not surprising therefore that there is a growing interest in the data deriving from cellular network to support traffic parameters estimation without requiring expensive and complex installations of ad-hoc measurement systems.

Looking at the results of the previous section, the first evidence that can be pointed out is that all the projects so far are independently carried out, lacking any kind of cohesion among each other. Most studies are from telecommunications or electronics researchers, not from transportation researchers, and sometimes there are ambiguities in the definition of the traffic parameters to be obtained. More or less each of them proposes a different method to obtain a traffic parameter given a mobile phone parameter. This means that the *fil rouge* mentioned in the introduction unfortunately has not been individuated.

However, all authors of the main reviews and applications in the field agree in considering that the following main issues affect any kind of study that would imply the estimation of traffic parameters from mobile phone data: issues regarding sample size and reliability, privacy, the role of private companies, and the role of transportation agencies (Caceres et al., 2008; Rose, 2006). Usually these aspects are considered separately in the literature, but actually they are strictly tied one with another.

Sample size and reliability

The possibility to exploit huge amounts of data from each person who carries a mobile phone in her pocket seems to solve the problem of small sample sizes, or at least it appears that having a sufficient sample size has a very competitive cost compared to expensive loop detectors field tests or camera surveys.

However, it is not unusual that having lots of data could result in an indiscriminate use of them, regardless of their quality or of their peculiar meaning. According to the reviewed literature, there are different aspects to be clarified in order to identify the factors on which the right sample size depend, and they relate all to the moment of the data collection, or at least, to the modality of obtaining this data.

First of all, the survey method or technology may influence the composition of the sample, which may be constituted by on-call phones only or by idle phones as well. Of course, having one or the other case drastically changes the size of the sample. The use of a sample of only on-call mobiles would guarantee higher accuracy, due to the stronger signal that the network receives from an active phone.

The survey area also has an impact on the sample size: if the data is collected on a motorway stretch, it is more likely that all the mobile phone surveyed are those inside the vehicle, which it is not true for surveys carried out on streets in densely urbanized areas. Reliability of the sample is also related with the possibility to exclude from the survey the mobile phones carried by people that are not inside the vehicles, but simply walking, or travelling by bike, or by public transport, or inside a building.

Another issue that affects sample size and its reliability regards the difference between data coming from the real GSM network, without informing the subscribers using their ordinary mobile phones (e. g., data used in RealTime Project by MIT), or data coming from ad-hoc surveys in which mobile users are informed and perfectly aware that they are being observed and agree in being tracked (e.g., the Mobile Century Project). In the first case data are collected at a GSM network level, and therefore they cover big portions of the transportation network as well. However, data should be anonymised, hence it is not possible to have any kind of control on them: this is the reason why so far this kind of data have been used only to obtain information about the behavior of aggregated groups of people and to study urban density and activity patterns, not to retrieve detailed traffic information. In the second case the sample may be more reliable and useful to obtain traffic information, but of course it is smaller.

Finally, it is also possible that the cell phone in a car is used by a passenger. The presence of two, three passengers, each of them making a call with their own mobile, leads to the uncertainty of counting the same car several times as the number of mobile phones that are inside it.

Clarifications are undoubtedly needed about the techniques to use in order to post-process the acquired raw data and isolate only the usable ones.

Privacy

Besides technological and market developments, the adoption of location and sensor technologies is influenced by security and privacy issues. In terms of privacy it is especially the tracking of people or goods transported which raises many privacy issues (Beinat et al., 2008). The use of mobile phone data from GSM network involves the cooperation of the carrier that provides them. This falls within the legal framework governed by regulations to protect the privacy of phone subscribers (Caceres et al., 2008). As defined by (Westin, 1970) "Privacy is the claim of individuals, groups or institutions to determine when, how, and to what extent information about them is communicated to others, and the right to control information about oneself even after divulgating it". In this definition a person's privacy corresponds to the control of that person's information.

The phone data used should be handled in an aggregated and anonymous way so as to not break the law on private data protection. To respond to perceived privacy concerns telecoms carriers may have also adopted an 'opt in' policy. Hereby users have to explicitly agree if their mobile phone may serve as a probe or must be excluded from the monitoring.

The role of private mobile companies

In order to exploit the advantages with respect to traditional survey methods, Wireless Location Technology has to be carried on in agreement with private mobile carriers, so as not to have to organize ad hoc surveys with a limited number of informed users, but using all the universe of subscribers. In this case, another question arises. How many mobile carriers are active in an area? Most of the projects found in the literature, which could make use of this kind of data, have agreements with only one mobile carrier. What about the rest of the population, which makes use of different mobile company for their communications?

This issue is mostly taken into account only with "coefficients" that consider the market penetration of that particular mobile company. Therefore, sample size depends also on the willingness of the mobile carriers to make data available.

Another aspect to be discussed is that most of the research carried out in this field is, indeed, confidential matter of private companies, or restricted by agreements and patents. Maybe in the future, it will be possible to make use of this information, and new horizons will open for researchers, such as it happened when the military "Selective Availability" of GPS signal was ended by US in 2000, and a big amount of highly-accurate and reliable location data resulted available to civil institutions.

The role of transportation agencies

Governments and public authorities play an important role in stimulating both the development and implementation of wireless location technology to support traffic management, or to support their demand. There are a number of issues that need to be addressed like regulation on privacy, road safety, data ownership, performance requirements, interoperability, market structure and of general economic services. In Fontaine et al (2007) it is argued that transportation agencies have historically not defined suitable performance requirements for wireless location systems. Many deployments have lacked a well developed independent evaluation that quantitatively assessed the system performance. As a result, most projects were developed as a 'technology push' rather than technology which support the demand side. The symbiosis of business needs and IT capabilities creates the potential for a surveillance infrastructure, namely dataveillance. "Dataveillance is the systematic use of personal data systems in the investigation or monitoring of the actions or communications of one or more persons" (Clarke, 1988). Dataveillance is a key concern in the adoption of location and sensor services where the government acts as the data collection hub. While regulations already provide a strict framework that, on paper, provides a high level of protection for individuals, this does not eliminate the concern that data collected for a legitimate traffic management use may eventually find other applications, either in the future or under different public order and safety circumstances.

On the other hand, transport agencies need to balance between a broad range of issues for creating the good conditions to stimulate the market to develop new technology. These include the individuation of suitable performance requirements for wireless location systems so that validation studies can base their efforts on these target values. For transport agencies it is useful to collaborate in the early stage of promising research and development projects to understand the possibilities and limitation of the technology.

CONCLUSIONS

In this paper a broad overview of the present state of the art of the research in the field of the use of data from GSM network for the estimation of traffic parameters has been provided. Though not going into the analytical details of how data are extracted from the cellular network, and how traffic parameters are estimated from cell-phone parameters, an articulated discussion of the main issues involved in this field of research has been given, raising many research questions, partly derived from the literature, but not yet or only marginally addressed, and partly coming from personal considerations.

Since the GSM network was commercially launched in 1991, there have been indeed many studies and field tests carried out during the last 15 years with the original start of the CAPITAL project in 1994. The literature can be subdivided in two types of references: individual research groups that have prepared ad-hoc surveys for testing their own data processing and estimations, and big projects with use of extensive datasets of cell phone data ad-hoc surveyed or coming from agreements with telecom operators.

The following general conclusions can be drawn:

- Travel speed and travel time are the most studied estimation issues in traffic management purposes;
- Projects are often initiated by technology providers, telecom operators and transport agencies. Validation studies are mostly carried out by research institutions;
- The adoption is still limited and it is a field still largely dominated by research and development. Technology is promising but not yet developed to the degree necessary for large scale utilization;
- Most of the studies focus on stretches of roads, or loops, and not on a road network level;
- Recent studies show better results; however transportation agencies have historically not defined suitable performance requirements for wireless location systems, which causes ambiguities in validation studies to draw clear conclusions.
- Active systems like GPS-equipped phones used in Mobile Millenium project, where thousands of users agree to place these phones in their vehicles in order to transmit positioning data and receive free live traffic information, look very promising.
- Extraction of telecom network data for the analysis of the spatial network activity patterns used in the projects Real-time Rome and Current City Amsterdam opens new possibilities in using such aggregated data for traffic management.

Data from cellular phones undoubtedly open new and important developments in transportation engineering but this requires their careful analysis. Hence, there are a number of steps needed to achieve a significant confidence in the use that can be made of these data. First of all, indeed, data should be validated. For traffic management related activities, this validation can be made by comparing data obtained from cell phones with data collected with other “on-site” systems like for example video-cameras. Obviously this should be done in different road conditions (freeways, arterials, urban roads) in order to understand the possible range of applicability. Another way to validate data collected could be to compare density of people obtained with census data during periods with a higher probability to have people at home (for example, the early evening or the Sunday afternoon, depending on the social context).

This paper is the first step of a study whose aim is to further investigate data deriving from the project Current City Amsterdam; the next phases of the research will include the development of a validation methodology of this data using loop detector data as ground truth, and the study of new applications in the field of traffic management. Especially for contingency management (e.g. traffic accidents, network disturbances caused by terror attacks or nature catastrophes) the use of cellular phone data may be of strategic importance in the future.

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